ARG Austrian Reports on Gravitation

ARG-2022-02

# GRAVITATIONAL COLLAPSE: AN OVERVIEW

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Keywords: Gravitational collapse of classical and newer models, free fall, singularities, black holes, hybrid models.

Abstract: We investigate classical and newer models that describe a gravitational collapse. In our previous work, we examined well-known models using mathematical methods based on the use of rods and clocks. As a result, we obtained coordinate-invariant equations, which, however, revealed some contradictions. We also discuss in detail the possibility of black holes and singularity formation.

Contents



## 1. INTRODUCTION

We examine the results of numerous authors who dealt with gravitational collapse. We restrict ourselves to stellar objects that are preferably surrounded by a Schwarzschild field.

We make some assumptions and remarks that we believe to be useful in building a collapsing model:

A. We consider models with singularities to be unphysical. Singularities are points or areas where mathematics fails.

B. There is no 'collapsing metric'. It has been known since Gauss that the line element on a surface can only describe the curvature of this surface, but not the change in this curvature. In order to mathematically record a collapse, one needs further information that can be obtained from the geometry or the Bianchi identities.

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C. The lack of sufficient information about the collapse has the consequence that in many papers one or more variables remain unspecified. The cause of this incompleteness is usually not questioned. Rather, some assumptions are made about the missing quantities in the hope of obtaining a physically practicable solution. Computer techniques are also used to adjust variables.

D. The question has to be clarified whether the metrics in use can be geometrized, i.e., whether the metrics can be assigned to comprehensible surfaces.

E. Most approaches to collapsing models result in the contraction of the stellar object below the event horizon of the exterior Schwarzschild field and in forming a singularity - a black hole. Whether there are naked singularities, i.e., singularities that can be experienced by an observer who is outside the event horizon, is contradictorily discussed in the literature.

F. We also consider whether and which linking conditions are specified at the boundaries between interior and exterior solutions.

# 2. FALL THROUGH THE EVENT HORIZON

Most authors, dealing with a gravitational collapse of a non-rotating star, assume that the collapsing object is surrounded by a Schwarzschild field, described by the standard Schwarzschild metric

$$ds^2 = \frac{1}{1-2M/r}dr^2 + r^2 d\vartheta^2 + r^2\sin^2\vartheta d\varphi^2 - \left(1-2M/r\right)dt^2. \qquad (2.1)$$

From this relation, it can be seen that a singularity occurs at the location $r = 2M$, i.e., at the event horizon. It has been discussed extensively in the literature whether this is a coordinate singularity or a real physical singularity. Since we feel that the term singularity is inaccurately defined, we circumvent the problem with a few considerations.

A coordinate singularity can be removed by introducing other coordinates. Here, we present as an example the coordinates of Einstein and Rosen [1]

$$ds^2 = \frac{R^2+16M^2}{16M^2}dR^2 + \left(\frac{R^2+16M^2}{8M}\right)^2 d\Omega^2 - \frac{R^2}{R^2+16M^2}dt^2, \qquad (2.2)$$

where $d\Omega^2$ is the abbreviation for the lateral differentials. Here, R is the Cartesian extra coordinate in the flat embedding space and $R = 0$ corresponds to $r = 2M$. Also the isotropic coordinates

$$ds^2 = \left(1+\frac{M}{2\bar{r}}\right)^4\left(d\bar{r}^2 + \bar{r}^2 d\vartheta^2 + \bar{r}^2\sin^2\vartheta d\varphi^2\right) - \left(\frac{1-\frac{M}{2\bar{r}}}{1+\frac{M}{2\bar{r}}}\right)^2 dt^2, \quad r = \left(1+\frac{M}{2\bar{r}}\right)^2\bar{r}. \qquad (2.3)$$

are frequently used. A look at the line element shows that the metric is regular over the entire region $0 < \bar{r} \le \infty$, whereby $\bar{r} = 0$ is also located at infinity. More detailed information on the relations between Schwarzschild coordinates and isotropic coordinates can be found in our monographs [2]. The region $r < 2M$ cannot be described with coordinate systems used in (2.2) and (2.3).

The metric (2.1) can be geometrized, i.e., a surface can be assigned to it, which clearly shows the geometrical properties of the model. The surface is known as Flamm's paraboloid, a 4th-order surface. It is a one-shell paraboloid of revolution that has its waist at $r = 2M$. This is the end of the geometry, the surface cannot be continued into the region $r < 2M$.

Let us return to the question of why the position is called a physical singularity. Every object approaching the event horizon from infinity or an arbitrary position in free fall would reach the speed of light at this location. Gravity becomes infinite there and time no longer passes. These are remarkable properties that appear important to us when dealing with a gravitational collapse. In this light, the event horizon seems to be not only a geometric barrier but also a physical one.

Nevertheless, many authors believe that the event horizon can be crossed. There was a long-lasting discussion among the authors Abramowicz, Agnese, Baierlein, Barceló, Bronikov, Cavalleri, De Sabbata, Dirac, Dymnikova, Gautreau, Gershtein, Pavšič, Katz, Kluzniak, Liberatis, Krori, La Camera, Lasota, Logunov, Loinger, Janis, Spinelli, Jaffe, Mazur, McGruder III, Mestvirishvili, Mitra, Öpik, Recami, Royzen, Shah, Shapiro, Sonego, Teukolsky, and Tereno. Paul, Lynden-Bell, Salzmann, and Visser [3-48]. We have summarized these arguments and counter-arguments in [2]. Mitra [49] describes in his textbook the historical development of the doctrine of the black hole. He brings several counter-arguments and lists numerous authors, including very prominent ones, who rejected the existence of black holes and briefly summarizes the arguments of these authors. He also supplements the representations with his own research results.

One of the best-known attempts to use a new coordinate system to discover regions of the Schwarzschild model that are still unknown, even below 2M, originates from Kruskal [50] and Szekeres [51]. However, in a paper [52] we have shown that the Kruskal method has little new to offer on this topic. If we depart from the coordinate description and constrain ourselves to reference systems that represent rods and clocks, we are again limited to the region $r > 2M$ in the Kruskal system as well. What is new is that the Kruskal system defines a new version of velocities for observers. Like free fall, this velocity is linked to geometry. It is obtained by converting the coordinate transformation into a Lorentz transformation. The latter defines a relative velocity that starts from zero and increases to the speed of light at infinity. We called the accompanying acceleration the Kruskal acceleration.

In their textbook the authors Misner, Thorne, and Wheeler [53] (MTW) believe that objects that move in free fall from infinity or any position to the event horizon can cross it in finite proper time while an observer at infinity concludes that the object only approaches the event horizon asymptotically and that it takes an infinitely long time to do so. We dealt with this contradicting statement in a talk in Berlin, using simple words. Here we want to repeat the essentials.

We simplify the derivation presented by MTW on several pages by removing quantities that are not directly used and detach ourselves from the term 'energy in infinity' introduced by MTW. What remains is a five-line that leads to the results of MTW. From its simple structure, one can see that the derivation is incorrect.

The authors examined a line element that mixes the arc elements of a comoving observer with those of a non-comoving observer. While the speed of an object coming from infinity in free fall is geometrically determined using $v = -\sqrt{2M/r}$, the speed $v'$ of an observer coming from any position $r_0$ must be derived by relativistically subtracting the speed at $r_0$ from the speed related to infinity:

$$v' = v(r, r_0) = \frac{-\sqrt{\frac{2M}{r}} - \left(-\sqrt{\frac{2M}{r_0}}\right)}{1 - \sqrt{\frac{2M}{r}}\sqrt{\frac{2M}{r_0}}}. \tag{2.4}$$

By mixing the arc elements, MTW obtain an expression for the velocity of fall related to $r_0$, which contradicts the laws of the special theory of relativity. We have clearly shown this in the following graphic:

MTW

$$ds^2 = dx'^2 - dT''^2$$

$$v' = \sqrt{v''^2 - v_0^2}, \quad \alpha' = \frac{\alpha''}{\alpha_0}$$

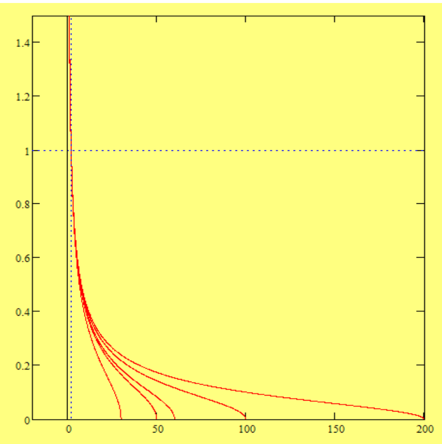


Fig. 9. Fall velocity from any position

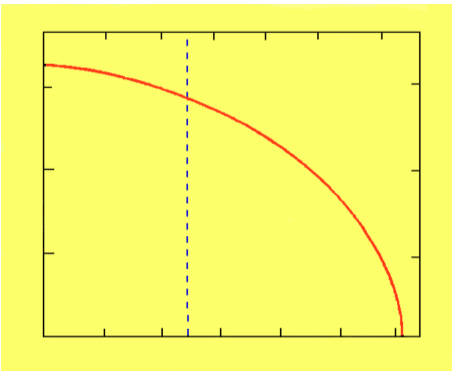

Fig. 11. Proper fall time

Strictly relativistic

$$ds^2 = dx'^2 - dT'^2$$

$$v' = \frac{v'' - v_0}{1 - v''v_0}, \quad \alpha' = \alpha''\alpha_0(1 - v''v_0)$$

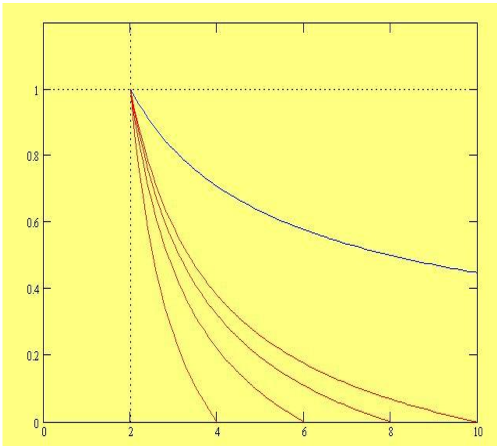


Fig.10. Fall velocity from any position

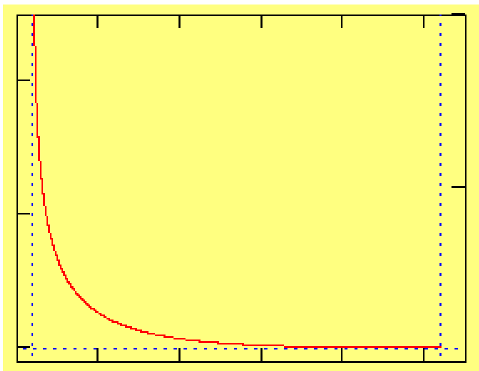

Fig. 12. Proper fall time

It can be seen that the fall velocity presented by MTW winds elegantly through the event horizon (dashed line) and becomes infinite at $r = 0$. The point $r = 0$ is reached after a relatively short time. In the strictly relativistic representation, the fall velocity reaches the speed of light regardless of the starting position at $r = 2M$, whereby an infinite amount of time passes.

After the foregoing, it is clear that the event horizon is an impenetrable barrier for collapsing models when the central object is surrounded by a Schwarzschild field. Every point on the surface of a collapsing star can be identified with a point moving radially in the Schwarzschild field. In the case of a star made of incoherent matter, the pressure of which is thus neglected, the above considerations can be directly applied. A star with pressure, which cannot contract arbitrarily, defines a limit that is possibly above 2M. Using some well-known models, we will explore this problem in the next sections.

# 3. HISTORICAL MODELS

In 1939 **Oppenheimer and Snyder** [54] presented what is now known as the work that founded the theory of black holes, although the term 'black hole' was introduced much later. The OS model is made up of a collapsing interior and a static exterior solution. The exterior part is the Schwarzschild exterior solution which, based on Birkhoff's theorem, remains static even when the field-generating stellar object collapses.

The OS model builds on an existing expanding / contracting cosmological solution by Tolman. The stellar object consists of incoherent dust with homogeneous density. Since in this case there is no internal resistance to contraction, the object can no longer be static. It collapses due to its gravitational forces. A completely pressure-free star is physically unrealistic. In the case of a collapse, the particles of a star finally come so close that pressure can be expected at a sufficiently high density. However, a pressure-free stellar object can approximately describe a dying star. When the thermonuclear processes inside a star have died down, it gives way to its gravitational attraction and collapses. The just discussed simplification to $p = 0$ has mainly practical reasons. The integration of Einstein's field equations without this condition leads to considerable difficulties, and an appropriate analytical solution is difficult to find.

The paper of OS initiated the research on gravitational collapse and was accordingly frequently cited. However, no one has attempted to examine this paper for its physical content. We have made up for this in four papers [55-58] and presented it clearly in [2].

In our first considerations, we closely followed the original paper of OS, but soon introduced auxiliary quantities that are closely related to geometric ones. Both solutions, the interior, and the exterior were developed in two different coordinate systems: the one that is comoving with the collapse and the one that does not comove. The transition between the two systems in particular provides information about how the collapse is taking place and thus brings to light the inconsistencies of the model. Our first aim was to examine the quantities and relations of the OS model, to set them up anew, bring them into connection with familiar ones, and prepare a geometrical interpretation.

After some redesign, it was possible to identify the velocity of the collapsing star’s surface as the speed of an object moving in free fall in the Schwarzschild field. Further transformations show that the metric of the collapsing object can be expressed in comoving coordinates $\{r',t'\}$ in the form

$$ds^2 = \mathcal{K}^2\left[dr'^2 + r'^2\, d\vartheta^2 + r'^2 \sin^2\vartheta\, d\varphi^2\right] - dt'^2 . \tag{3.1}$$

Here, $\mathcal{K} = \mathcal{K}(t')$ is the scale factor that specifies the measure for the contraction. It connects the comoving and the non-comoving radial coordinates by using

$$r = \mathcal{K} r' . \tag{3.2}$$

In the line element (3.1) $t'$ is the global time that applies to all particles that participate in the contraction and thus the proper time of all participating observers. This means that the metric discussed above describes a *locally flat* space. The metric has a Lemaître form and is typical for freely falling objects. The lapse function is $g_{4'4'} = 1$. As a result, no gravitational forces act on the comoving observer, as is to be expected from Einstein's elevator principle.

The 4-beine can be read from the metric (3.1) and the field quantities can be calculated from the Ricci rotation coefficients:

$$'U_{m'} = \left\{0,0,0,\frac{i}{\mathcal{R}}\right\}, \quad B_{m'} = \left\{\frac{1}{r},0,0,\frac{i}{\mathcal{R}}\right\}, \quad C_{m'} = \left\{\frac{1}{r},\frac{1}{r}\cot\vartheta,0,\frac{i}{\mathcal{R}}\right\}, \tag{3.3}$$

provided we hold onto the original Minkowski notation $x^{4'} = i(c)t'$. The first three components of these quantities correctly reflect that the space is locally flat, i.e., free of gravity. The lateral field quantities B and C describe the curvatures of a surface. The 4th components of all three quantities are the tidal forces, which describe the compression of the particles inside. From a complicated expression of OS we calculated the quantity

$$\mathcal{R} = \mathcal{R}(t') = \sqrt{\frac{r_g^3}{2M}} \ . \tag{3.4}$$

$\mathcal{R}$ is half of the curvature radii of the Schwarzschild parabolae measured on the surface of the object. It can be interpreted as the radius of a spherical shell, which is part of the interior OS solution. $r_g$ is the value of the radial variable on the surface of the object.

Einstein's field equations are satisfied with the quantities (3.3). In the stress-energy momentum tensor, there is only the mass density

$$\kappa\mu_0 = \frac{3}{\mathcal{R}^2}\,, \tag{3.5}$$

an expression that occurs in this form in other gravitational models. All other components of the stress-energy momentum tensor vanish. With (3.4), we also can use the expression

$$\kappa\mu_0 = \frac{6M}{r_g^3}\,.$$

From this, it can be seen that for $r_g \to \infty$ the mass density vanishes. The stellar object would have to have been infinitely large but massless at the time $t' = 0$ and still have filled an infinitely large cosmos.

OS have given an interior solution for collapsing objects

$$ds^2 = \alpha^2 dr^2 + r^2 d\vartheta^2 + r^2 \sin^2\vartheta d\varphi^2 + a_T^2 dit^2, \quad \alpha = \frac{1}{\sqrt{1-\frac{r^2}{\mathcal{R}^2}}}\,. \tag{3.6}$$

The expression $a_T$ is rather complicated, but on the surface, it accepts the corresponding expression of the exterior Schwarzschild solution. The first three arc elements of the metric (3.6) are identical to those of the interior Schwarzschild solution and describe a 3-dimensional spherical cap. Since all four metric coefficients at the boundary surface match those of the exterior Schwarzschild solution, the 1st linking condition is fulfilled.

OS did not specify the 2nd linking condition. It is often combined with the requirement that the first derivatives of the metric coefficients match at the boundary surface. Nariai and Tomita [59-61] examined the linking conditions for the OS model and were of the opinion that the interior OS solution is not well adjusted to the exterior Schwarzschild solution. They replaced the exterior Schwarzschild solution with a complicated one while maintaining the interior OS solution. They used the linking conditions by O'Brien and Synge. Leibovitz [62] disagreed and found the 1st linking condition to be valid, but did not address the 2nd one.

We have the impression that the commonly used linking conditions are not suitable for all models. Mitra [63] has not reported finding the common linking condition for the Schwarzschild model to be fulfilled and found a new interior solution that connects to the exterior one under these conditions. We [64] also investigated the problem and established a simple linking condition for the Schwarzschild model. It is required that not only the metric coefficients at the boundary surface should have the same values, also the tangents (cutting tangents) of both solutions should coincide. This is a requirement that is relatively easy to verify, as long as a model can be geometrized, i.e., both regions of the model can be represented by surfaces. The surfaces must touch each other and must merge smoothly, i.e., they must not have a kink. Thus, it is so that the continuity of the two OS regions is still worth discussing.

OS also specified the relation between the comoving time t' and the time t of an observer at rest. Thus, a matrix can be formulated for the transformation between the comoving and the non-comoving coordinate systems. Finding such a transformation is eventually tedious. Probably for this reason other authors did not specify such a coordinate transformation for their models, or it was not possible to set up a coordinate transformation, because the model does not have an analytical solution. The primary purpose of using special coordinate systems is to provide the simplest possible basis for calculations. The great advantage, however, is that such a coordinate transformation is accompanied by a Lorentz transformation which contains velocity parameters. Once such a Lorentz transformation has been found, one also has the *physical* velocity of the collapse at hand, if one relates it to the velocity at the surface of the collapsing stellar object.

The metric (3.6) satisfies Einstein's field equations. The stress-energy-momentum tensor in the non-comoving system contains currents of matter and is covariantly conserved. Although the exterior solution in the comoving system of OS is formally different from the Schwarzschild representation, it can be converted into the standard Schwarzschild form with a transformation that is very similar to the Lemaître transformation. It is obvious that the event horizon represents an insurmountable barrier, because the collapse velocity of the surface of the object, which can be read from the above-mentioned Lorentz transformation, exceeds the velocity of light at this location.

OS showed with an approximation that after a certain stage of the collapse, no light can be emitted from this object, but there are no limits to the collapse. Mitra [65] [66] contradicted this. He found that in addition to a missing factor ¼, the relevant quantity in this approximate relation has the wrong sign. He concluded that the OS model cannot provide any evidence of a black hole.

The stellar OS object would have an infinitely large extension in its initial state, collapses in free fall, and leaves empty space behind, in which a Schwarzschild field spreads. On the other hand, the collapse velocity at the event horizon would reach the velocity of light. This can be ruled out by the relativity principle. The force of gravity and the tidal forces would be unlimited there. No star can exist under these conditions. Due to these considerations, the OS model cannot be used as a base model for a black hole.

**McVittie** [67] dealt with a class of collapsing solutions, introducing the methods of cosmology to gravitational physics. He also dealt with an ansatz with $p \neq 0$. In this case, the pressure and energy density become infinite after a finitely long time, and the inward speed of the fluid elements also becomes infinite. The example shows the difficulty of setting up a collapsing model with non-vanishing pressure. We therefore only treat McVittie's cases with $p = 0$.

McVittie starts with the metric

$$ds^2 = \mathcal{K}^2 \left[ \frac{1}{1 - k \frac{r'^2}{\mathcal{R}_0^2}} dr'^2 + r'^2 d\Omega^2 \right] - dt'^2 . \tag{3.7}$$

Here, the *curvature parameter* k takes the values

$$k = \{1, 0, -1\} . \tag{3.8}$$

The scale factor $\mathcal{K}$ depends on the time, while $r'$ and $t'$ are the comoving coordinates referring to the collapse. For $k = 0$, one gets the already discussed OS model. We [2] also examined the other two cases, with less satisfactory results. They are *hybrid* models. On the one hand, the lapse function has the value $g_{4'4'} = 1$ in the time-like part of the metric (3.7). Thus is $t'$ the global time that applies equally to all points of the collapsing object. No gravitational forces can be derived from the lapse function. This is the typical property of free fall. Thus, one must assume that the object McVittie is looking at collapses in free fall and that the space must appear *locally flat* to an observer who is comoving with it, in accordance with Einstein’s elevator principle. However, the values $k \neq 0$ define a local spatial curvature. This can also be seen when calculating the field quantities from the Ricci rotation coefficients:

$$B_m = \left\{ \frac{a_l}{r}, 0, 0, -\frac{i}{\mathcal{K}} \dot{\mathcal{K}} \right\}, \quad C_m = \left\{ \frac{a_l}{r}, \frac{1}{r} \cot\vartheta, 0, -\frac{i}{\mathcal{K}} \dot{\mathcal{K}} \right\}, \quad U_m = \left\{ 0, 0, 0, -\frac{i}{\mathcal{K}} \dot{\mathcal{K}} \right\}. \tag{3.9}$$

Here, $a_l = \sqrt{1 - k \frac{r'^2}{\mathcal{R}_0}}$ is the factor that indicates the deviation from the locally flat geometry. Only for $k = 0$ is $a_l = 1$ and the space appears to be flat. The 4$^{th}$ components of the quantities correctly reflect the change in volume that surrounds any point of the collapsing object. The first three components commonly correspond to an observer who does not participate in the contraction. The equation (3.9) shows a mixture of comoving and non-comoving components. We, therefore, refer to models that collapse in free fall and have mixed components as *hybrid*. Thus, it can be seen that the geometrical and physical structure of a model can be examined with the help of the tetrad method and the Ricci rotation coefficient.

In his textbook [68], **Weinberg** discussed a gravitational collapse in detail. Like McVittie, Weinberg assumed a line element of type (3.7) and obtained a pressure-free model for the case $k = 1$. The model is *hybrid* as well. The field quantities have mixed components analogous to (3.9), which results in a rather complicated expression for $\dot{\mathcal{K}}$. In [2][69][70], we formally extended Weinberg's annotations and obtained the common expression $\kappa\mu_0 = 3/\mathcal{R}^2$ for the mass density, where is $\mathcal{R}$ the radius of a spherical cap, which is described by the spatial part of the metric (3.7). Weinberg calculated the collapse time from $\ddot{\mathcal{K}}$. After a finite time, the spherical cap shrinks to a point with an infinitely high mass density. At the end of the collapse, no time is passing.

Weinberg also specified a non-comoving coordinate system, which makes it possible to set up a matrix for a coordinate transformation connecting these systems and to assign a Lorentz transformation to it. The relative velocity and the Lorentz factor can be read from the Lorentz transformation. If these quantities are related to the surface of the object, values are obtained that differ considerably from the special theory of relativity:

$$\alpha_{col} = \frac{\sqrt{1-\frac{2M}{r'_g}}}{\sqrt{1-\frac{2M}{r_g}}}, \quad v_{col} = -\frac{\sqrt{\frac{2M}{r_g}-\frac{2M}{r'_g}}}{\sqrt{1-\frac{2M}{r'_g}}} . \tag{3.10}$$

The development of the collapse is reminiscent of MTW graphics in Fig. 1 and Fig. 3. At the beginning of the collapse, the initial velocity $v_{col} = 0$ and the Lorentz factor $\alpha_{col} = 1$ as the consequence of $r_g = r'_g$. At $r_g = 2M$, i.e., when the surface of the stellar object has reached the event horizon of Schwarzschild geometry, is $v_{col}(r_g = 2M) = -1$ and $\alpha_{col} = \infty$. The collapsing object has reached the velocity of light in free fall and the surface would move faster than the velocity of light after having crossed the event horizon, whereby the force of gravity first becomes infinite and then imaginary.

Weinberg's model is not a realistic representation of a process that can take place in Nature.

# 4. THE COLLAPSE OF SCHWARZSCHILD'S INTERIOR SOLUTION

It is noticeable that when trying to describe a gravitational collapse, it is usually assumed that the collapsing object is reasonably surrounded by a Schwarzschild field. According to Birkhoff's theorem, this field remains unaffected by any change in the extension of the field-generating object. Numerous approaches were made for the metrics of this object and the two linking conditions to the exterior Schwarzschild solution were sought or sometimes circumvented. Apart from one unsuccessful attempt by Narlikar [71], we are not aware of any further attempts that derive a collapsing model with the help of the interior Schwarzschild solution as a starting model. A 100 years later Karl Schwarzschild published his solutions, we [72] attempted to figure out a collapsing model based on the interior Schwarzschild solution.

The question arises as to why the problem was not addressed much earlier. There may be some reasons for this: The representation of the Schwarzschild interior solution was chosen unfavorably and did not give any clue of a collapse, the geometric background of the metric was not worked out, the mathematical effort is considerable and there were compunctions that one has to detach from the fascinating idea of black holes. One could have known since 1916 that the complete Schwarzschild solution, consisting of the interior and exterior solution, definitely rules out the formation of black holes.

We did not approach the theory of collapse by solving Einstein's field equations, but rather we assembled it from existing geometric elements.

Therefore, we try first to work out the geometrical basis of the Schwarzschild interior solution and then turn to the collapse. The metric can be written in *canonical* form

$$ds^2 = \frac{1}{\sqrt{1-\frac{r^2}{\mathcal{R}^2}}} dr^2 + r^2 d\vartheta^2 + r^2 \sin^2\vartheta d\varphi^2 - a_T^2 dt^2 . \tag{4.1}$$

Here, $r$ is the radial coordinate and $\mathcal{R}$ the radius of a spherical cap, which is described by the spatial part of the metric. $a_T$ is the lapse function. The curvature parameter $k = 1$ can be read off. Thus, the geometry is positively curved. With the fundamental relation

$$r = \mathcal{R} \sin\eta \tag{4.2}$$

(4.1) takes the form

$$ds^2 = \frac{1}{\cos^2\eta} dr^2 + r^2 d\vartheta^2 + r^2 \sin^2\vartheta d\varphi^2 - a_T^2 dt^2 \tag{4.3}$$

where $\eta$ is the polar angle of the spherical cap.

We note the time-like metric coefficient in the original Schwarzschild form

$$a_T = \frac{1}{2}\left(3\cos\eta_g - \cos\eta\right). \tag{4.4}$$

Here, the marker g denotes the value of a quantity at the boundary of the two geometries. In order to better understand the metric (4.1), we use the original Minkowski notation $dx^4 = i(c)dt$ and write

$$idt = \rho_g di\psi . \tag{4.5}$$

Here, $\rho_g$ is the radius of curvature of the Schwarzschild parabola at the boundary surface of the interior and exterior geometry. Although Flamm's paraboloid has largely entered the literature, significant findings were not drawn from Flamm's work, probably because the paper is written in German. We refer to an important relation by Flamm [73]:

$$\rho_g = 2\mathcal{R} . \tag{4.6}$$

The radius of curvature of the Schwarzschild parabola is twice as long at the boundary surface as the radius of the spherical cap of the interior geometry. Thus, we have explained the factors ½ and 3 in (4.4) and are now defining:

$$a_T idt = \left[\left(\rho_g + \mathcal{R}\right)\cos\eta_g - \mathcal{R}\cos\eta\right] di\psi . \tag{4.7}$$

Here, $\left(\rho_g + \mathcal{R}\right)\cos\eta_g$ and $\mathcal{R}\cos\eta$ are the radii of two (open) concentric pseudo-circles and the flow of time corresponds to an imaginary circular ring sector. At the boundary $\eta = \eta_g$, the relation $a_T idt = \left[\rho_g \cos\eta_g\right] di\psi$ is obtained. This expression can be converted into the well-known Schwarzschild term. This shows that the 1st linking condition is also fulfilled for the time-like metric coefficient. We presented the 2nd linking condition in detail in [64].

Flamm’s relation (4.6) proves to be exceedingly useful for understanding gravitational collapse. It has proven suitable to assume that the collapsing object can be represented by a series of self-similar spherical caps that slide down Flamm's paraboloid while maintaining the 2nd linking condition. This means that the spherical cap and the Flamm's paraboloid always have a common cutting tangent. We have shown this in Fig. 5.

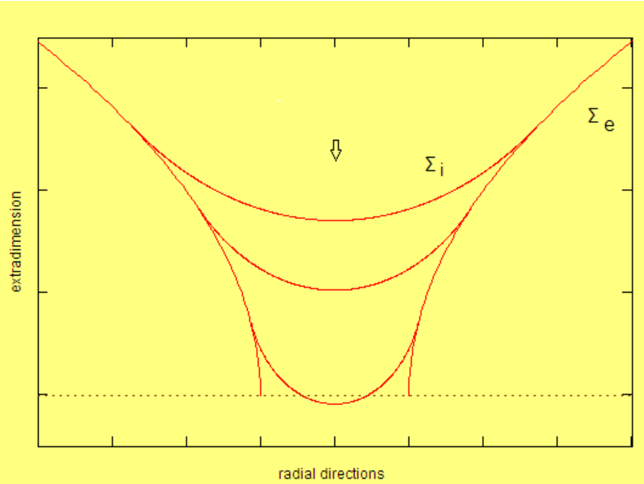


Fig. 5. The collapse

At each point in time of the collapse, the Schwarzschild parabola defines according to (4.6) the curvature and extent of the spherical cap. Lastly, this means that the gravitational collapse cannot be derived from a 'collapsing metric', instead its development is determined by the surrounding of the collapsing object.

As Schwarzschild has already stated, the pressure inside the object is given by

$$\kappa p = -\frac{3}{\mathcal{R}^2} \cdot \frac{\cos\eta - \cos\eta_g}{\cos\eta - 3\cos\eta_g}. \tag{4.8}$$

It has a critical value when $\cos\eta_g = \frac{1}{3}$. In the center of the star ($\eta = 0$), the pressure becomes infinite at the critical aperture angle $\eta_g$. From this one calculates [2] the lower limit for the possible extent of the star as

$$r_g^m = 2.25M, \quad r_g > r_g^m. \tag{4.9}$$

Thus, the interior solution has an inner horizon. This means that there is no non-rotating star in the universe that is smaller than $2.25M$. Thus, the inner horizon is always above the event horizon and the complete Schwarzschild model downgrades the event horizon to a mathematical artifact. It also follows that a collapsing star can only reach this horizon asymptotically, as we will mention later.

The collapse velocity is made up of two components according to Einstein's law of addition:

$$v_C = \frac{v_R - v_I}{1 - v_R v_I}, \quad v_R = -\frac{r}{\mathcal{R}_g}, \quad \mathcal{R}_g = \sqrt{\frac{r_g^3}{2M}}, \quad v_I = -\frac{r'}{\mathcal{R}_0}, \quad \mathcal{R}_0 = \sqrt{\frac{r'^3_g}{2M}}. \tag{4.10}$$

On the surface of the star is $v_R^g = -\sqrt{2M/r_g}$, thus, identical to the velocity of an observer in free fall from infinity in the exterior Schwarzschild field. From this, $v_I^g = -\sqrt{2M/r'_g}$ is subtracted relativistically. The velocity of the surface of the collapsing star is therefore always smaller than that of the freely falling observers in accordance with $a_T \neq 1$. At the beginning of the collapse the values are $r_g = r'_g$, $\mathcal{R}_g = \mathcal{R}_0$, and thus, $v_C^g = 0$. The structure just discussed is analogous to Figs. 2 and 4. However, the curve of the collapse time approaches the inner horizon $r_g^m = 2.25M$ asymptotically.

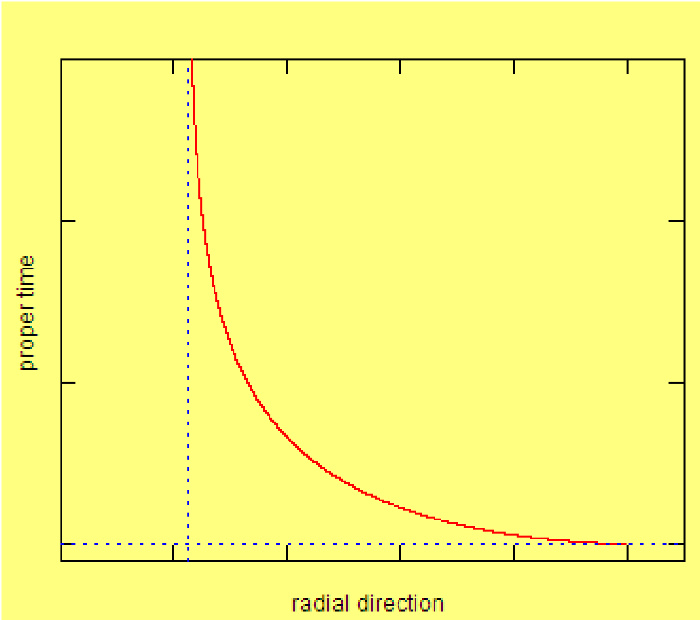


Fig. 6. Evolution of the collapse

The collapsing Schwarzschild solution describes an 'eternally collapsing object' (ECO). The term ECO was introduced by Mitra [74] for several reasons from astrophysics. The interior Schwarzschild solution is closely connected to the exterior one via Flamm's relation (4.6). Without Flamm's relation, any geometric interpretation is possible. Thus, the interior Schwarzschild solution is the first candidate to describe a collapse.

In [72] we illustrated the relation between the velocities. For $v_l = 0$ one gets the pressure-free OS model. The field quantities of the Schwarzschild interior are derived using the projector technology developed in [2]. From the equation (4.10), one can calculate the Lorentz factor and set up a Lorentz transformation that mediates between the comoving and non-comoving reference systems. As expected, the lateral field quantities do not appear to be flat, but contain 4$^{th}$ components, the tidal forces. Since there is no free fall, gravity does not vanish in the comoving system.

The complete Schwarzschild solution, consisting of the interior and exterior solutions with or without collapse, describes a singularity-free model that does not allow any black hole, singularities or naked singularities. A discussion about cosmic censorship, the no-hair theorem, or Hawking radiation is superfluous.

# 5. SUMMARY

We have presented an overview using three classical models that deal with the methods of gravitational collapse commonly used in the literature. We contrasted these models with our model of the collapsing interior Schwarzschild solution. In the attached bibliography, we mention and comment on numerous other approaches, but note that most authors assume that black holes and singularities are possible. However, the bibliography does not claim to be complete. References to other models can be found in the quotations of the papers.

# 6. LITERATURE


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# 7. BIBLIOGRAPHY

**Abrahams** and **Evans** found a critical parameter for the formation of a black hole when an axisymmetric object collapses. They used numerical methods.

**Acquaviva** et al. studied the thermodynamic properties of black hole formation and the change in gravitational entropy in an Oppenheimer-Snyder-Datt collapse.

**Adler** studied collapsing shells of incoherent light or zero dust and spheres of a perfect fluid. Some with pressure while, some with non-uniform density. To obtain black holes, he used the metrics in Eddington-Finkelstein and Kruskal coordinates, as well as in Painlevé and Gullstrand form.

**Ali** assumed a fairly general metric for a dust model. After collapsing into a black hole, the particles inside and outside are said to have different horizons. This allows particles falling into a black hole from the outside to interact with the particles inside it.

**Ames** and **Thorne** described the spectral distribution of radiation from a star collapsing through the event horizon.

**Banerjee** discussed naked singularities that can be observed by an external Schwarzschild observer.

**Banerjee** studied an inhomogeneous spherical distribution of dust. He started from a general spherical approach. His interest was in the singularity $g_{11} = r^2 = 0$, where, the radial separation vanishes, although the circular distances remain finite. At this location, the mass density becomes infinite.

**Banerjee** presented a class of solutions for a fluid sphere with radial heat flow. He put on the line element of the interior solution with time-dependent parameters, but specified the linking condition to the exterior Vaidya metric, which contains a cross term. The special thing about the solution of BCD is that during the collapse the surface of the object does not meet a horizon, but eventually a (naked) singularity is formed.

**Banerjee** noted that the naked singularities found by Yodzis et al. were described in one of his earlier papers.

**Banerjee** and **Banerji** found a class of exact interior solutions for a spherically symmetric fluid. An initial outward motion is reversed. Then, a collapse to a singularity of infinitely high mass density takes place. There are cases where the initially collapsing system bounces back so that a singularity is avoided.

**Barreto** studied the influence of viscosity on a gravitational collapse of a radiating sphere. He started with the Vaidya metric, but transformed the components of the stress-energy-momentum tensor into an orthogonal reference system to interpret them physically. The equation of state of the model shows the extent of anisotropy caused by viscosity. He went into little detail about an exterior field and the linking conditions: the radial pressure at the boundary of the viscous sphere does not vanish.

**Barreto**, **Herrera**, and **Santos** extended the concept of the adiabatic index, which measures the stiffness of the equation of state for adiabatic systems, to systems that emit or absorb energy. The collapse of two radiating models was studied.

**Barve** described a simple method to determine whether or not a collapse of spherically symmetric dust can form a naked singularity.

**Barve**, **Singh**, and **Witten** derived the acceleration of a fluid element during a spherical collapse of a perfect fluid with tangential pressure. They obtained singular and naked singular solutions.

**Bhattacharya** et al. applied the stress-energy-momentum tensor to a massless scalar field and specified the collapse conditions.

**Bayin** found some time-dependent solutions of a radiating fluid sphere. The stress-energy-momentum tensor is the sum of the stress-energy-momentum tensors of a perfect fluid and radially expanding radiation. The changes over time were assumed to be so slow that a quasi-static approximation was sufficient.

**Bekenstein** studied a collapsing charged sphere joining the exterior Reissner-Nordström solution. The question raised whether the charge can prevent a total collapse.

**Bergmann** derived a new metric from the Schwarzschild metric with coefficients satisfying the condition $g_{11}g_{44} = 1$ but with the other metric coefficients being constant. Then he brought the metric into an isotropic form and concludes a possible collapse.

**Bini** and **Mashhoon** studied time-dependent gravity models and their collapse scenarios. They related the motion of the particles to the gravitational collapse. An axial collapse and plane gravitational waves were treated.

**Biroukou** et al. described a formalism and a numerical approach for a spherically symmetric scalar collapse in arbitrary dimensions and with the cosmological constant.

**Bizoń**, **Chmaj**, and **Schmidt** studied 4+1 dimensional Einstein field equations that allow for gravitational waves with radial symmetry. The gravitational collapse was investigated using numerical methods.

**Bondi** started from a general spherical symmetric ansatz, with metric variables depending on r and t. He calculated the stress-energy momentum tensor in general forms and used local Minkowski coordinates, which we call tetrads. He assumed observers moving with a radial velocity and represented the stress-energy-momentum tensor in comoving and non-comoving frames. Finally, he neglected the time dependence of the metric variables in the spatial components of the stress-energy-momentum tensor. In this way, he was able to show that the configuration is static at all times. For the sequence of the static models, he obtained relations from the stress-energy momentum tensor.

**Bonnor** and **Faulkes** found an exact interior solution for an adiabatic spherically symmetric motion of a perfect fluid with uniform density but non-uniform pressure. The solution is connected to the exterior Schwarzschild solution with a moving surface.

**Bonnor**, **Oliveira**, and **Santos** dealt extensively with the problem of a radiative spherical collapse. They also discussed the interesting case where the pressure balances the heat flow, so that matter can be in free fall.

**Brady** raised the question of whether a scalar field collapse can create a zero-mass black hole.

**Brady** considered the collapse of a homothetic scalar field. Using a mixture of analytical and numerical methods, he showed that there are two classes of solutions with black holes and naked singularities.

**Brady** et al. performed numerical studies of gravitational collapse for stiff fluids. They constructed the critical solution as a scalar field solution using a self-similar approach.

**Brito** et al. studied a cylindrically symmetric inhomogeneous collapsing model. They obtained an exact solution, which can be transformed into an already known solution for $\Lambda = 0$.

**Brustein** and **Medved** investigated whether the Buchdahl bound of the interior Schwarzschild solution can be prevented by introducing negative pressure.

**Cahill** and **Taub** envisaged a spherically symmetric model that allows for a conformal transformation. The metric coefficients were applied as a function of time.

**Carr** et al. considered a spherical collapse of a self-similar solution. They focused on the equation of state $p = \alpha\mu$ and showed that the global nature of the solutions is sensitive to $\alpha$.

**Chakraborty** and **Chakraborty** described a cylindrically symmetric gravitational collapse of an anisotropic perfect fluid connected to an exterior cylindrically symmetric solution. The radial pressure does not vanish at the surface of the fluid. Gravitational waves originate outside of the fluid.

**Chan** proposed a model for a collapsing radiating star with shear motion and radial heat flow. At the beginning of the collapse, the pressure is isotropic but becomes anisotropic due to the shears. Because the star radiates away all of its mass during the collapse, neither a black hole nor a naked singularity is formed.

**Chan** described a collapsing model of isotropic fluids with shear viscosity, heat flow, and radiation. The initial isotropic pressure becomes anisotropic during collapse due to shearing. The quantities introduced in the stress-energy-momentum tensor remain undetermined.

**Chan** presented the model of a collapsing radiant star with heat flow. He analyzed the density, pressure, and luminosity. The exterior metric is the Vaidya metric.

**Chan** found an analytical solution to Einstein's field equations for the collapse of the radiating body consisting of an isotropic fluid with shear and radial heat flow.

**Chan** obtained further results for an isotropically collapsing body described by Kolassis and Santos. He found a connection between radiation density and heat flow.

**Chan** proposed a collapsing radiating star composed of a shearing fluid with bulk viscosity. The star emits heat flow and radiation. Initially, the pressure is isotropic, but steadily becomes anisotropic. The problem is solved numerically.

**Chan**, **Herrera**, and **Santos** studied the effects of shear and shear viscosity on dynamic instability.

**Chan, Herrera,** and **Santos** studied instabilities concerning local anisotropy and radiation. Anisotropy can drastically change the stability of the system.

**Chan** and **da Silva da Rocha** studied the collapse of thick spherical shells composed of self-similar shear-free fluid with heat flow. All energy conditions are satisfied and naked singularities emerge.

**Chan** et al. studied the effect of heat flow on the dynamic instability of a non-adiabatic spherical collapse.

**Chandrasekhar** studied the stability conditions for a radially oscillating gas sphere where the baryon number is said to be preserved.

**Chandrasekhar** introduced the term 'highly collapsed' and attempted to obtain numerical results.

**Chase** studied the case of a thin shell of a charged surface. Under optimal conditions, the system is stable. The instability starts at a certain critical radius, which is always much higher than the gravitational radius of the Nordström model.

**Chakraborty** and **Chakraborty** considered a cylindrically symmetric collapse of a perfect fluid connected to an exterior cylindrically symmetric solution using the Darmois junction condition. The radial pressure of the anisotropic fluid does not vanish at the boundary and is related to the shear viscosity.

**Chakraborty**, **Chakraborty,** and **Debnath** studied quasi-static Szekeres models with perfect fluid and with tangential stresses and anisotropic pressures. The gravitational collapse has been considered.

**Chakravarty**, **Choudhury,** and **Banerjee** found general methods to obtain exact solutions to Einstein's field equations. They also allow time-dependent metric coefficients.

**Chatterjee** and **Banerji**, following a paper by Liang, described three classes of non-rotating collapsing dust models.

**Chiba** suggested a spindle-shaped naked singularity in a prolate collapse. The problem was solved analytically and numerically.

**Chirenti** and **Saa** studied the charged Vaidya metric in double-zero coordinates. In these one can describe a non-statically charged black hole with varying mass and charge. Naked singularities appear.

**Choptuik** reckoned all the numerical studies for a spherically symmetric collapse of a massless scalar field and found a critical parameter for the formation of a black hole.

**Clément** and **Fabbri** presented a collapsing solution in 2+1 gravity with the cosmological constant minimally coupled to a massless scalar field.

**Christodoulou** equipped collapsing models with a scalar field, showing that naked singularities are possible.

**Christodoulou** dealt with the collapse of an inhomogeneous spherical dust cloud and cosmic censorship.

**Christodoulou** treated a massless scalar field as a material model. Under certain conditions, a black hole is formed surrounded by a vacuum.

**Christodoulou** extensively examined the validity of cosmic censorship in the context of a spherical collapse of a scalar field.

**Cissoko** et al. studied a gravitational collapse using the cosmological constant. The linking conditions between static and non-static models were derived. Of the three apparent horizons, only two are physically significant: the black hole horizon and the cosmic horizon.

**Cocke** used the cylindrical form of the Friedmann metric to obtain an infinite cylinder of an incoherent fluid. The exterior metric is obtained by requiring that the 1st and 2nd fundamental forms are continuous at the boundary. The exterior metric is non-static and can be represented in Einstein-Rosen form.

**Condron** and **Nolan** studied scalar field solutions of cylindrical symmetry. In self-similar models, the metric is described by a set of variables.

**Consenza** et al.. The evolution of radiating spheres was studied. The field equations were numerically integrated for two models.

**Cook** studied comoving coordinate solutions of spherically symmetric fluids with spatially uniform density but not-uniform pressure. The sign of the spatial curvature of these models can vary over time. He believed that it is not necessary to know all the parameters of the models to record all the properties of space-time.

**Cooperstock**, **Jhingan**, **Joshi**, and **Singh**. Assuming the weak energy condition, they studied the nature of non-central self-focusing singularities that can arise in a spherical compact object in a gravitational collapse.

**Dandach** and **Mitskiévic** found families of metrics in synchronic coordinates that generalized Tolman metrics for perfect fluids with pressure. New arbitrary functions appear.

**Dai** and **Stoikovic** calculated the collapse of two different shells. One consists of dark matter and is completely transparent. The other consists of ordinary particles but is fully reflective. Based on Birkhoff's theorem, the interior of the shell is assumed to be flat.

**Das** and **Tariq** described a spherical collapse of an anisotropic fluid. They defined an equation of state and required Synge's linking condition for their solution. A black hole is formed, with the fluid remaining anisotropic and having positive energy, and 'radial' pressure. However, motion in the fluid is superluminal or tachyonic. The object is collapsing from infinity at a constant speed.

**Das**, **Tariq**, and **Aruliah** studied anisotropic fluids collapsing from infinity into a black hole. They assumed an equation of state and used Synge's linking condition. Within the event horizon, matter takes on an exotic state.

**Das** and **Kloster** found a class of exact solutions in Tolman-Bondi coordinates. At the boundary, the linking conditions of Synge-O'Brien and Israel are satisfied.

**Datt** studied spherical time-dependent solutions in a general form, which, however, leaves open two arbitrary functions of r.

**Datta** extended Einstein's and Strauss' rotating star model to a nonstatic one. Under certain circumstances, the system can collapse to a minimum volume and bounce.

**De** extended the Reissner-Nordström model with time dependence of the metric coefficients. The solutions of the charged Einstein field equations leave open one parameter that depends on r and one that depends on t. Specializations of these parameters lead to the charged static model or the OS model.

**Debnath**, **Chakraborty,** and **Barrow** studied naked singularities for a dust model with $\Lambda \neq 0$ in n+2 dimensions in the Szekeres model.

**Debnath**, **Nath,** and **Chakraborty**. The linking conditions between static and non-static models were studied in terms of gravitational collapse. The physical meaning of the apparent horizon was discussed and the cosmological constant was also considered.

**De la Cruz** and **Israel** considered a charged body surrounded by a thin shell of charged dust falling toward that body. The collapse is also possible if the shell has fallen below the event horizon. The problem was handled using an analytically extended Reissner-Nordström solution.

**De la Cruz**, **Chase,** and **Israel** studied a collapse with asymmetry. Magnetic dipoles and gravitational quadrupoles were analyzed.

**Demianski** and **Lasota** extended a model proposed by Bondi. During the collapse, the body contracts to zero volume and radiates all of its mass.

**Deshingkar**, **Joshi,** and **Dwivedi** studied the nature of the central singularity, which forms in a spherically symmetric collapse. There is always a strong curvature singularity, with the tidal forces diverging strongly.

**Deshingkar**, **Joshi,** and **Dwivedi.** Naked singularities emerge as the final state of an inhomogeneous dust collapse. Geodesics were dealt with in detail.

**Deshingkar** et al. studied the influence of the cosmological constants on the final state of a spherical inhomogeneous collapsing dust cloud. The initial data of a bounce in terms of density and velocity profile have been characterized in detail.

**De Oliveira** and **Santos** studied the linking condition for a magnetodynamic fluid with heat flow. The radiation is described by the Reissner-Nordström-Vaidya metric.

**De Oliveira**, **Santos,** and **Kolassis** treated a collapsing radiating star composed of a shear-free isotropic fluid with radial heat flow. The model has pressure, but free parameters remain open.

**De Oliveira** and **De Pacheco** studied the radiation pulses in optical, X-ray, and γ-ray domains resulting from a neutron star collapse.

**Di Prisco** et al. described a charged dissipative spherical gravitational collapse with shear. Viscosity effects are also addressed. Outside the fluid is a Reissner-Nordström-Vaidya field. The linking condition was adapted to this field.

**Di Prisco** et al. studied the linking conditions for a charged, dissipative collapse with shear and viscosity.

**Di Prisco**, **Herrera,** and **Varela** studied the fluctuations of local anisotropies of homogeneous, self-gravitating compact objects. The metric coefficients are time-dependent, but no analytical form is given.

**Di Prisco** et al. studied the influence of processes on the evolution of a radiating star before the system relaxes into diffusion.

**Di Prisco** et al. considered cylindrically symmetric metrics. The interior is a fluid with anisotropic pressure, the exterior a vacuum Einstein-Rosen metric connected with the Darmois linking condition.

**Di Prisco**, **Herrera,** and **Esculpi** studied a collapse of a radiating sphere with heat flow. They dealt with luminosity profiles and relaxation times.

**Doroshkevich**, **Zel'dovich,** and **Novikov** studied the collapse of non-symmetrical and rotating masses. They found that the properties of such collapsing matter are similar to those of a spherical collapse.

**Dündar**, **Arik,** and **Mirzaiyan** studied a gravitational collapse of a dust shell. Static and oscillating solutions have been found, as well as shells that never reach the singularity.

**Dwivedi** and **Joshi** studied a class of non-self-similar Tolman-Bondi dust collapse models. They have strong curvature singularities and violate cosmic censorship.

**Ellis** found the Schwarzschild theory unsuitable for the construction of a particle model. He envisioned a new geometry coupled to a scalar field. Its double-sided Schwarzschild construct allows for positive and negative mass and time-dependent quantities.

**Faulkes** studied solutions for inhomogeneous matter surrounded by a Schwarzschild field. He gave analytical expressions for pressure and energy density, which, however, contain arbitrary functions of time whose values are restricted by the linking conditions.

**Faulkner**, **Hoyle,** and **Narlikar** followed the solution of Oppenheimer and Snyder. They showed that a signal from an outside observer never reaches the surface of an object collapsing in free fall. They specified line elements in comoving coordinates for the interior and exterior of the object. The latter can be transformed into the standard Schwarzschild form. This interior metric differs significantly from the Schwarzschild interior metric.

**Fayos** and **Torres** build on the radiating Vaidya solution that describes the exterior field and matched an interior solution that radiates matter. This avoids singularities.

**Fayos**, **Jaén**, **Llanta,** and **Senovilla** connected a general spherically symmetrical radiating Vaidya metric with the Darmois linking condition and studied the time dependence of the model.

**Ferraris**, **Francaviglia,** and **Spallicci** criticized the limitations of the McVittie metric. The pressure is said to be infinite and the energy negative at the event horizon in astrophysical applications.

**Fimin** and **Chechetin** published a comparative study of the Hilbert and Schwarzschild metrics, and a collapse of the Tolman metric.

**Florides** found that a collapse of a spherical system with a mass of incoherent matter in the context of Newton's theory is identical to the relativistic results of Oppenheimer and Snyder.

**Foglizzo** and **Henrikson** studied the collapse of homothetic ideal gas spheres, where naked singularities appear. In the case of a plane collapse, singularities are absent.

**Fowler** -studied the stability of supermassive stars. He showed that a small contribution from rotation can be sufficient to avoid star instability.

**Frolov** constructed a self-similar solution of a continuous spherically symmetric collapse of a scalar field in n dimensions. Among them were also some closed-form solutions.

**Frolov** and **Pen** studied the global structure of a critical collapse model of a scalar field. They were able to integrate through the event horizon with no problems.

**Fujimodo** studied the collapse of a rotating gaseous ellipsoid. He assumed a suitable temperature distribution in the initial ellipsoid and adopted a special formula for the cooling rate of the gas.

**Gao** et al. found that the mass of a black hole can increase as it absorbs dark energy. The effect is said to have significance for astrophysics.

**Gao** and **Lemos** studied thin massive charged dust shells based on the Reissner-Nordström solution in higher dimensions.

**Garfinkle** and **Vuille** [studied a collapse with the cosmological constant. Space-time consists of two regions, one collapsing, the other inflationary.

**Ghezzi** extended the Reissner-Nordström solution to a time-dependent model and added an interior time-dependent solution. He dealt extensively with the junction conditions and comoving coordinate systems. He adjusted open parameters using numerical methods.

**Ghezzi** studied the stability of a charged neutron star. Black holes and naked singularities are formed.

**Ghosh** and **Beesham** studied the naked singularities in a gravitational collapse of an inhomogeneous dust cloud in a higher-dimensional Tolman-Bondi model. Higher dimensions favor black holes rather than naked singularities.

**Giacomazzo** et al. studied the collapse of a differentially rotating neutron star. Models with different angular momentum were examined. A rotating black hole resulted.

**Giambo** studied the conditions under which gravity coupled to a self-interacting scalar field. It determines the formation of a singularity.

**Giambo** et al.. In a gravitational collapse, the final state has been studied without simplifying assumptions. The authors used new methods based on non-linear techniques. Naked singularities form.

**Glass** considered the shear-free motion in a spherically symmetric perfect fluid. In the conservation law, he allows a time-dependent energy density. The field quantities provide an unspecified function that is related to the gravitational energy.

**Glass** and **Mashhoon** described a collapse around a core of a star. The collapsing region grows monotonically until the Schwarzschild horizon forms. The system could describe the final stage of a collapsing star cluster.

**Glass.** New solutions for a shear-free collapse with heat flow have been derived from known solutions for bound spherical perfect fluids. It was linked to the Vaidya solution.

**Glazer** generalized Chandrasekhar's pulsation equation for a charged homogeneous model. The influence of the electric charge on the dynamic stability was worked out.

**Gonçalves** and **Jhingan** analyzed a spherical dust collapse with non-zero radial pressure but zero tangential pressure. For certain values one gets an analytical solution. Occasionally, visible and invisible singularities arise.

**Gonçalves** and **Jhingan** found an analytical solution for a collapse of an infinitely long cylindrical shell, producing a singularity but no apparent horizon.

**Gonçalves**, **Jhingan,** and **Magli.** The final state - a black hole or a naked singularity - in a gravitational collapse with tangential stresses has been classified depending on the initial conditions and the equation of state.

**Govender** presented a dissipative collapse model with heat flow. The interior of the star is fitted to a generalized Vaidya solution. Variables remain undetermined.

**Govender** et al. presented a radial heat flow collapse leading to superdense cold stars. The model is connected to Vaidya's exterior radiation metric.

**Govender** et al. considered a collapse starting from an initially static configuration. Energy is dissipated by radial heat flow. It reflects that a singularity can never form and that the star mass is completely vaporized in a finite time.

**Govender** and **Thirukkanesh** studied a dissipative collapse with the cosmological constant. The exterior is represented by the Vaidya metric.

**Govender**, **Reddy,** and **Maharaj** studied a dissipative collapse of a radiating star with radial heat flow. They showed how shear affects collapse. These increase the temperature in the interior. The authors also gave the thermodynamic quantities for the interior of the star.

**Govender**, **Maharaj,** and **Martens** denote a particular collapsing model as causal. It is shear free and the interior connects to the exterior Vaidya solution. The heat of reaction leads to the self-consistent determination of the temperature. The collapse begins with an infinitely large radius and zero mass density.

**Govender**, **Martens,** and **Maharaj.** Results based on the perturbation of a static star show that relaxation effects contribute to a significant increase in the central temperature and temperature gradient.

**Govinder** and **Govender** continued their investigations concerning a radiative stellar collapse and presented two new solutions to the temperature equation and another result for nonzero acceleration.

**Govinder** and **Govender** presented an exact solution to the temperature equation and the temperature profiles of a collapsing star.

**Govinder** and **Govender** described a radiating star whose area radius during evolution is equal to its own radius. A new family of solutions describes the dynamic behavior of a Euclidean star. Singularities were avoided by appropriate choice of open constants.

**Goswami** presented a new class of solutions to Einstein's field equations for a spherical collapse of dust matter coupled to heat flow. They all bounce before reaching the singularity. The star explodes away to infinity.

**Goswami** and **Joshi** developed the theory of a collapse in n-dimensions. The final state of a stellar object is a singularity or a naked singularity, depending on the initial values chosen.

**Goswami** and **Joshi** constructed a class of perfect fluid models that have pressure and inhomogeneity. The formation of a black hole is imperative.

**Goswami** and **Joshi** showed how a collapse evolves from initial data. Given initial pressure and mass density, a black hole or naked singularity is formed depending on free functions and the equation of state.

**Goswami** and **Joshi** studied how pressure affects the fate of a continuous collapse. The pressure gradient is critical to black hole formation, trapped surfaces, and apparent horizons.

**Grammenos** performed a hydrodynamic treatment of a Friedman-type non-adiabatic spherical collapse. The conclusions are said to be consistent with the predictions of stellar evolution.

**Guha** and **Banerji** studied the dynamics of a cylindrical anisotropic fluid with dissipation in terms of heat flow, radiation and shear viscosity.

**Gundlach** and **Martín-García** referred to 'critical phenomena' for black hole formation.

**Gundlach** gave an overview of critical phenomena for gravitational collapse.

**Gundlach** presented in a detailed work a self-similar spherical collapse of a spherically symmetric fluid. The solutions are determined numerically.

**Gupta** solved Einstein's field equations for a pulsating fluid sphere, where the outer space is empty. Non-uniform pressure is intended to prevent singular states.

**Hamadé** and **Steward** reported a spherically symmetric collapse of a massless self-gravitating scalar field equation. The field either disperses to infinity or collapses into a black hole depending on the strength of the initial data. The problem is examined numerically.

**Harada** studied the adiabatic conditions and the equation of state for a perfect fluid collapse. The relativistic hydrodynamic equations are solved numerically using a retarded time coordinate.

**Harada** established a stability criterion for self-similar solutions of perfect fluids. He discussed the so-called 'kink mode'.

**Harada** examined the occurrence of singularities in general and referred to numerical methods. He highlighted the importance of self-similar solutions in a collapse.

**Harada**. A wide class of perfect liquids of self-similar solutions is unstable with respect to the so-called kink-mode.

**Harada** and **Maeda** probed the convergence of a collapse of self-similar solutions to Einstein's field equations using numerical methods. The formation of black holes and singularities depends on the fine-tuning of the initial data.

**Harada**, **Iguchi,** and **Nakao** showed that collapse emits explosive radiation, creating a naked singularity.

**Harada**, **Iguchi,** and **Nakao** studied the collapse of a spherical cloud of counter-rotating particles. A central singularity arises depending on the rotational moment of the rotating particles.

**Harada**, **Nakao,** and **Iguchi**. The metric functions that describe a spherically symmetric model can be integrated explicitly. if the radial pressure of a model vanishes. The nakedness and curvature strength of the singularity was examined.

**Hawking** and **Penrose** noted that singularities are to be expected when either the universe is spatially closed or an object is collapsing. It is assumed that large mass concentrations are inevitably unstable.

**Henrikson** and **Wesson** found solutions for non-static dust clouds. For stiff equations of state, the solutions were solved numerically.

**Hernández** et al. considered the development of self-gravitating spheres, assuming a static auxiliary solution. They explored the possibility of analytical and numerical solutions. Ultimately, they were limited to a post-static procedure.

**Hernández** et al. treated the linking conditions for radiating spheres with heat flow.

**Hernandez**, **Núños,** and **Percoco** found that under certain circumstances a spherically symmetric mass distribution can satisfy a non-local equation of state. The problem was solved numerically.

**Hernandez** and **Misner** studied inward-moving matter with respect to trapped surfaces using hydrodynamic methods. They used observer time coordinates, resulting in cross terms in the metric.

**Hernandez** and **Di Prisco** presented a numerical model for a collapsing radiating sphere. Under certain physically reasonable conditions, the collapse can bounce.

**Hernandez** and **Di Prisco** extended the Lemaître-Tolman-Bondi model for the dissipative case. Scalar functions appear in the orthogonal decomposition of the Riemann.

**Herrera** considered a family of self-gravitating spheres, where the radial forces in individual regions of the spheres have different signs. This was explained by a local anisotropy of the fluid or by the emission of incoherent radiation. Einstein's field equations were calculated from a general central symmetric approach and then specialized to an anisotropic fluid with different radial and tangential pressures. Isotropic and unpolarized emission of energy density was envisaged.

**Herrera** showed that a change in the Weyl tensor is necessary as a prerequisite for a spherically symmetric fluid to leave the state of equilibrium.

**Herrera**, **Martin,** and **Ospino** studied anisotropic fluid spheres with a time-dependent lapse function. However, an analytical form of this is not given.

**Herrera** and **Santos** described a dissipative gravitational collapse based on the Misner-Sharp approach. The notion of mass density always depends on the internal thermodynamic state.

**Herrera** and **Santos** anticipated a non-comoving system, with the metric coefficients also being time-dependent. They gave the solution to Einstein's field equations in a general form and brought the stress-energy-momentum tensor into tetrad form. They assumed a radial velocity $\left(v \ll c\right)$ with which the object under consideration collapses very slowly. They transformed into the comoving system. They explored different definitions of energy for the interior of the object.

**Herrera** and **Santos** investigated the properties of fluid spheres in which the area radius and the proper radius match. They called such stars Euclidean and showed that they cannot be static. They described their exterior field with the Vaidya metric.

**Herrera** and **Santos** described in detail the local anisotropies of self-gravitating systems, also treating contracting models.

**Herrera** and **Santos** studied a spherically symmetric solution with radial heat flow. They showed that a temperature gradient arises, which can be traced back to perturbations.

**Herrera** and **Santos** described an anisotropic cylindrical collapse of a perfect fluid. The radial pressure does not vanish at the surface of the cylinder.

**Herrera**, **le Denmat**, **Santos,** and **Wang** studied some general properties of a spherical shear-free collapse. They demanded conformal flatness and discussed the relation between dissipation and inhomogeneous density.

**Herrera** et al. extended the Misner-Sharp approach to a collapse of the viscous dissipative case. They found that neutrino emission is necessary to overcome a star's binding energy to form a neutron star or black hole.

**Herrera** et al.. A self-gravitating spherical fluid with anisotropic stresses has been studied. The connection to the Weyl tensor, shear, and anisotropic pressure was analyzed.

**Herrera** et al. dealt with a collapse with inhomogeneous mass density. Parameters remain undetermined.

**Herrera** et al. analyzed the heat conduction of a relativistic fluid when it leaves the hydrostatic equilibrium.

**Herrera** et al.. Five scalar quantities, which are obtained by orthogonal decomposition of the Riemann, determine the development of self-gravitating spherically symmetric dissipative fluids with anisotropic stresses.

**Herrera**, **Di Prisco,** and **Ospino** presented some analytical solutions for radiating collapsing spheres. Neutrino radiation creates a neutron star or black hole.

**Herrera**, **Di Prisco,** and **Ospino** studied the stability of the shear-free condition using the evolution equation for a spherical-symmetric, anisotropic, viscous, dissipative fluid distribution. They started from a general metric and calculated the field quantities.

**Herrera**, **Di Prisco,** and **Fuenmayor** found an expression for the active gravitational mass, the $\gamma$-metric, after it has left hydrostatic equilibrium. Even small deviations from sphericity result in significant changes of the active mass.

**Herrera** and **Di Prisco** found the active gravitational mass of a relativistic, heat-conducting fluid after it has left hydrostatic equilibrium.

**Herrera** and **Di Prisco** studied axisymmetric, shear-free, dissipative configurations. There is a connection between the magnetic part of the Weyl tensor and the vorticity.

**Herrera** and **Di Prisco** performed a general study on the collapse of axisymmetric sources, in particular for anisotropic dissipative fluids. The problems were solved both analytically and numerically.

**Herrera**, **Jiménez,** and **Ruggieri** found a general method to describe nonstatic, radiating fluid spheres. They used numerical methods to solve Einstein's field equations.

**Herrera**, **Dermat,** and **Santos** studied the dynamic instability of a non-adiabatic spherical collapse with dissipation in the form of radial heat flow.

**Herrera** and **Martinez.** Two relativistic models for collapsing spheres have been studied. The relaxation time determines the bounce or collapse of the sphere.

**Husain**, **Martinez,** and **Núñez** found exact spherical-symmetric solutions, which can be interpreted as an inhomogeneous dynamic scalar field. They have black holes and white hole-like regions with trapped surfaces.

**Iben** considered a quasi-static equilibrium of a massive star. As the internal temperature increases and the radius decreases, the binding energy first passes through positive values and then rapidly decreases to negative values.

**Israel** presented an analytical completion of Vaidya's radiation metrics. An irreversible collapse into a point takes place.

**Israel** conjectured that singularities do not form in an asymmetric collapse, or that collapse has oscillatory effects that prevent it from reaching the event horizon.

**Israel** dealt extensively with cosmic censorship and naked singularities.

**Israel** announced a confinement theorem that forbids the formation of naked singularities in a gravitational collapse.

**Ivanov.** An effective anisotropic spherically symmetric heat flow fluid model can absorb the additives of two perfect fluids with anisotropy, heat flow, bulk and shear viscosity. In most cases, heat flow can be avoided more effectively.

**Ivanov** gave a review of collapsing shear-free fluid spheres with heat flow.

**Ivanov** treated shear-free anisotropic fluids, relying on two formulas for the mass function and involving a master potential. The models lead to equations with undetermined quantities.

**Jebsen**. This work is an early attempt to find time-dependent, spherically symmetric solutions to Einstein's field equations. However, he showed that with such a general approach, the model again is reduced to a static one by a suitable choice of the time coordinate.

**Jhingan** described the structure of a gravitational collapse of spherically symmetric dust using the Tolman-Bondi-Lemaître metric. The formation of black holes and naked singularities depends on the initial dates.

**Jhingan** and **Kaushik** studied the collapse for a Lemaître-Tolman-Bondi model. Under certain conditions, singularities are globally visible.

**Jhingan**, **Joshi,** and **Singh** complement previous work on the importance of the initial density and velocity distribution in a spherical collapse.

**Jhingan**, **Dwivedi,** and **Brave** studied whether energy can physically escape from the regions of naked singularity and reach a distant observer.

**Jhingan** and **Magli** examined the Einstein-Strauss cluster for the collapsing case. The final state can be a black hole or a naked singularity.

**Joshi** calculated the collapse in general terms in spherical coordinates and discussed recent developments in the formation of black holes and naked singularities.

**Joshi** presented the problem of gravitational collapse in detail and dealt with the question of whether naked singularities can occur.

**Joshi** et al. developed procedures to establish equilibrium configurations that arise at a final state of gravitational collapse with regular initial conditions. The collapsing fluid has only tangential pressure. The equilibrium geometries can either be regular or have a naked singularity at the center.

**Joshi** and **Dwivedi** studied naked singularities of an inhomogeneous collapse of a Bondi-Tolman dust cloud. Self-similar and non-self-similar cases were considered. Two unspecified functions remain.

**Joshi** and **Dwivedi** showed that strongly curved naked singularities can occur in a self-similar gravitational collapse and the weak energy condition is satisfied.

**Joshi** and **Dwivedi** described a continuous dust collapse. The final state of the collapse depends on the initial data. The free variables of the solution decide whether a black hole or a naked singularity is formed.

**Joshi** and **Goswami**. Initial conditions cause naked singularities or black holes as the final state of continuous gravitational collapse.

**Joshi** and **Goswami** studied a gravitational collapse with negative pressure and weak energy condition. A trapped surface could be avoided.

**Joshi** and **Goswami** found that the occurrence of singularities indicates the breakdown of Einstein's theory. They described a model that avoids singularities, with the entire mass of the stellar object being radiated away.

**Joshi** and **Goswami** considered singularities and black hole paradoxes at classical and quantum levels. Problems could be solved by avoiding trapped surfaces in a continuous collapse. This is the case when the star radiates all of its mass.

**Joshi** and **Królak** studied the naked singularities in the Szekeres model, which describes irrational dust and is a generalization of the TLB model.

**Joshi** and **Malafarina** extended the Oppenheimer and Snyder model with small tangential stresses. This changes the final state of the collapse from a black hole to a naked singularity.

**Joshi** and **Malafarina** extensively studied the formation of black holes and naked singularities in a gravitational collapse.

**Joshi** and **Singh.** A spherical inhomogeneous collapse of a dust cloud, described by a Tolman-Bondi model, leads to either a black hole or a naked singularity, depending on the original density distribution.

**Joshi**, **Dadhich,** and **Maartens** investigated the physical conditions under which a naked singularity is more likely to form than a black hole. Sufficiently strong shear effects near the singularity force the formation of an apparent horizon.

**Joshi** and **Dwivedi** studied the structure and evolution of naked singularities in a self-similar collapse for an adiabatic fluid. Conditions were given as to whether the singularities were either locally or globally naked.

**Kanei** described a collapse using the Painlevé-Gullstrand metric. He wanted to use the same coordinate system to describe the collapse inside and outside the event horizon. The star collapses in free fall from a certain position. The collapse speed conflicting with the special theory of relativity has the MTW structure.

**Karmakar** investigated class one embeddings, where the metric coefficients can also be time-dependent.

**Kriele** discussed the initial value problem of a spherically symmetric star with a general equation of state.

**Knutsen** studied nonstatic spheres with pressure gradients. He concluded that pressure-free models are unphysical and that singularities should be surrounded by a trapped surface.

**Knutsen** claimed that there must be at least two horizons for a sphere of fluid, the Schwarzschild horizon and the apparent horizon inside matter.

**Knutsen** found a solution for a spherically symmetric fluid in non-comoving coordinates. It contains shear, pressure, and the density which is positive within the fluid. The speed of sound is less than the speed of light and decreases towards the outside.

**Knutsen** found a singularity-free model for a spherically symmetric nonstatic fluid with uniform density but nonuniform pressure.

**Kolassis**, **Santos,** and **Tsoubelis** considered a spherical fluid with heat flow radiating zero fluid into the outer region described by the Vaidya metric. They gave a Friedman-like exact solution of Einstein's field equations for the interior, which describes a physically usable collapse.

**Kramer** describes a collapse with radial heat conduction. The Vaidya radiation field is used as an exterior solution. The motion of the boundary is derived from the linking condition.

**Krori** and **Borgohain** extended the results of other authors with regard to non-static solutions of Einstein's field equations for radiating spheres. They received contracting and bouncing models.

**Kuchowicz** studied very general relativistic fluid spheres, also making an ansatz with time-dependent metric coefficients. However, the parameters of the model remained undetermined.

**Kurita** and **Nakao** studied a collapse of a 0-dust with cylindrical symmetry. Naked singularities are created along the axis of symmetry, with the 0-dust being emitted again from the naked singularities.

**Kuroda** studied naked singularities in the Vaidya model in a spherical collapse of pure radiation.

**Lake** and **Hellaby** showed that a radiating Oppenheimer-Snyder model can have naked singularities.

**Lake** and **Hellaby.** A reply.

**Lake** described the influence of the cosmological constants on the collapse of a spherically symmetric inhomogeneous dust sphere.

**Lake.** General conditions for the formation of naked singularities in a spherical collapse have been derived. He claimed that naked singularities do not violate the spirit of cosmic censorship.

**Lake** set up the equations of motion of thin timelike shells using embedding theory.

**Lake** examined two possible types of singularities in the Tolman model.

**Lake** examined the possibility of naked singularities in a non-self-similar collapse.

**Landau** studied the stability of stars. He objected to attributing properties to stars just to simplify the mathematical treatment.

**Lapiedra** and **Moralis-LLadosa** analyzed pressure-free, inhomogeneous matter with spherical symmetry and a spatial foliation of comoving 3-spaces. The solution has two arbitrary functions of the radial coordinate, which are determined with the Lichnerowicz linking condition to the exterior Schwarzschild solution.

**Laserra** treated a pressure-free spherical system. In particular, the initial conditions for the evolution of a system over time.

**Lasky**, **Lun,** and **Burston** considered spherical dust and showed, with a [3+1] decomposition, that the metric coefficients are completely determined by the matter distribution. Shell-crossing singularities are investigated.

**Leibowitz** presented time-dependent spatially symmetric solutions. A class indicates that a condensation or evaporation process is taking place on the object's surface.

**Leibowitz** and **Israel** addressed the question of what is the maximum amount of energy that can be radiated from a collapsing star.

**Lemos** showed that naked singularities formed in a spherical gravitational collapse with radiation are the same as those formed in a matter collapse.

**Lemos**. A gravitational collapse in the AdS background was studied. Massless singularities arise for a highly inhomogeneous collapse. Toroidal, cylindrical, and planar collapse can be treated together.

**Letelier** and **Wang** described the collision and interaction of cylindrically symmetrical fluids. Analytical solutions lead to naked singularities.

**Lim** and **Zhang** inspected a dust shell or two collapsing onto an existing black hole. The interior of the shells is time-dependent. The flow of time slows down during the collapse.

**Lin**, **Mostel,** and **Shu** investigated a collapse of a uniform, non-rotating, pressure-free spheroid. The initial eccentricity increases steadily due to the anisotropic gravitational field. An initially oblate spheroid tends to be a disc, and a prolate one to be a spindle. The problem was treated numerically.

**Lynden-Bell** and **Bičák** found some inhomogeneous solutions with increasing condensation and black holes.

**Maeda** published a higher dimensional gravitational collapse with perturbation effects from quantum gravity.

**Madhav**, **Goswami,** and **Joshi** studied a collapse of a tangential pressure cloud of matter in the presence of the cosmological constants. They examined how $\Lambda$ modifies the dynamics of collapse and whether it has an influence on cosmic censorship.

**Magli** studied anisotropic elastic spheres whose dynamics are supported only by tangential stresses. The solutions contain three arbitrary parameters that have been related to the distribution of mass and energy, and elastic internal energy.

**Magli** analyzed the internal dynamics of a spherically symmetric star made of elastic material. The charged case was also treated.

**Magli** dealt with an exact solution describing the dynamics of an elastic anisotropic sphere. The presence of tangential stresses cannot make visible a dust singularity.

**Maharaj** and **Govender** studied a dissipative collapse of a magneto-dynamic fluid with heat flow and shear.

**Maharaj** and **Govender** referred to Kramer's radiating star. Einstein's field equations are supplemented by a further differential equation.

**Maharaj**, **Govender,** and **Govender** studied the behavior of a radiating star surrounded by a Vaidya field. The external stress-energy momentum tensor is a superposition of a zero fluid and a string fluid.

**Mahajan** and **Joshi** studied a spherical collapse with zero radial pressure but tangential pressure. Either a black hole is formed or the star disperses.

**Malafarina** and **Joshi** studied the formation of black holes and naked singularities considering thermodynamic effects.

**Malafarina** and **Joshi** used a general formalism to describe a spherical collapse in which the radial pressure vanishes but the tangential pressure does not. A black hole can pass over to a naked singularity.

**Marshall** modified the metric by Oppenheimer and Snyder in such a way that no trapped surfaces occur.

**Mansouri** claimed that no spherically symmetric solution of Einstein's field equations describes a uniform collapse of a fluid sphere and that satisfies the equation of state $p = p(\mu_0)$ except for the trivial case $p = 0$.

**Martinéz** introduced a method to study thermal conduction and viscous processes in a collapse. Two partial differential equation systems have to be solved; Einstein's field equations and the Maxwell-Cattaneo transport equation.

**Martinéz**, **Pavón,** and **Núñez** treated the evolution of an anisotropic radiating shell with zero stress. The increase in anisotropy makes it possible to divide the interior of the sphere into three concentric zones that differ in the amount of interactions between matter and radiation.

**Markovic** and **Shapiro** studied the effect of a positive cosmological constant on a spherical collapse to a black hole. They considered several solutions and followed the model of Oppenheimer and Snyder.

**Mashhoon** and **Partovi** made a very extensive study on spatially isotropic solutions to the Einstein-Maxwell equations considering an equation of state that relates pressure and matter density. Analogies to Newton's theory were made.

**Mashhoon** and **Partovi** described the collapse or expansion of a charged perfect fluid. Collapsing models can be interpreted as a charged fluid surrounding a black hole. The singular region in matter is either spacelike or null.

**May** and **White** found numerical solutions for models with simplified equations of state using computer technology. They described a state of stellar material in a late phase of collapse. This is triggered by the gravitational field and the pressure of the matter.

**Mena** gave an overview of the collapse of cylindrical-symmetric black hole models.

**Mena**, **Natário,** and **Death** connected a collapsing inhomogeneous and spatially homogeneous but anisotropic solution to an exterior static solution with negative cosmological constants and planar or hyperbolic metrics.

**Mena** and **Tavacol** studied the initial data for an inhomogeneous spherical dust collapse that can lead to a black hole or a naked singularity. For naked singularities, the initial data must be centrally homogeneous. The authors start with an LTB model.

**Mena** and **Nolan.** Necessary conditions for the existence of naked holes have been derived. Geodesics starting from a singularity have been described.

**Mena** and **Oliveira** studied the linking conditions between FLRW and generalized Vaidya models with spherical, planar, and hyperbolic geometry. They found new models with negative cosmological constant and electromagnetic radiation.

**Michael** referred to a work by Hoyle and Fowler studying strong sources of radiation. They found that the energetic destruction of a star is also possible without being triggered by rotation. The hydrostatic equilibrium is disturbed by a neutrino loss and leads to quasi-homologous contraction.

**Miller** considered a quasi-stationary collapse of a class of slowly rotating non-homogeneous bodies and compared it with the results for non-rotating bodies.

**Mimoso**, **Le Delliou,** and **Mena** studied a spherically symmetric model of an anisotropic fluid with expanding and collapsing regions. They used a [3+1] decomposition.

**Misner** and **Sharp** considered matter with a stress-energy-momentum tensor of an ideal fluid. They generalized the Oppenheimer-Volkhoff equation for hydrostatic equilibrium by including an acceleration term and a contribution to the effective mass of a shell of matter that comes from its kinetic energy. For the time-dependent case, this gives the change in the total energy of each fluid sphere. It arises from the work done on this sphere by the surrounding fluid. The fluid is under pressure and therefore, does not collapse in free fall. The collapsing system was adapted to the exterior Schwarzschild solution.

**Misner** studied the dynamic equations of a self-gravitating shell of an ideal fluid with heat transfer. The internal energy is converted into neutron flux.

**Misra** and **Srivastava** studied an adiabatic collapse of a uniform density sphere, both neutral and charged. There are inconsistencies in the charged case.

**Misra** and **Srivastava** studied the non-static Einstein-Maxwell equations with incoherent matter as a source. the role of electrical forces during a spherically symmetric collapse was discussed.

**Misthry**, **Maharaj,** and **Leach** studied the collapse of a radiating star for the case that the Weyl tensor vanishes. Non-linearities are assumed at the boundary. Numerous non-linear solutions, which also included heat flow, could be given.

**Mitra** showed that a gravitational collapse must be accompanied by the emission of radiating energy, independent of certain properties of the collapse.

**Mitra** pointed out that astrophysical considerations rule out a continuous collapse into a black hole. Rather, an ECO (Eternally Collapsing Object) is created.

**Mitra** showed that no trapped surfaces can arise in a relativistic collapse, although this result does not depend on the equation of state or other details.

**Mitra** proved that trapped surfaces are not possible in a gravitational collapse. He also used Kruskal coordinates and Lemaître coordinates to substantiate his point.

**Mitra** found that the pressure inside the star plays a more important role than is generally assumed. It can prevent trapped surfaces.

**Mitra** compared a continuous collapse resulting in infinite space curvature where the collapse speed exceeds the speed of light with an eternally collapsing object (ECO) where the collapse speed is always $v < c$.

**Mitra** proved that for a non-static, adiabatically evolving sphere, a homogeneous density also requires an isotropic homogeneous pressure.

**Miyamoto**, **Jhingan,** and **Harada** investigated the weak cosmic censorship in a gravitational collapse within the framework of the LTB solution with regard to astrophysical applications.

**Morgan** described the radial implosion along one axis of an axisymmetric model. In the null-fluid approximation, the metric is regular everywhere.

**Musco**, **Miller,** and **Polnarev** numerically calculated the formation of black holes using the perturbation method.

**Müller zum Hagen** et al. studied naked singularities, borrowing from Misner and Sharp's equations for perfect fluids.

**Müller** and **Schäfer** studied the fate of matter falling into a black hole, reducing matter to a thin spherical shell.

**Naidu**, **Govender,** and **Govinder** studied the causal temperature profile of a radiating star undergoing dissipative gravitational collapse without forming a horizon.

**Naidu** and **Govender** studied the effects of pressure anisotropy and heat dissipation of a radiating collapsing star. The exterior solution is in Vaidya form. Darmois' relations were used for the linking condition.

**Nakao** extended the Oppenheimer-Snyder model with the cosmological constant. The interior then corresponds to the closed FRW model, the exterior to the Schwarzschild-de Sitter model.

**Nakao** and **Morisawa** studied the collapse of a cylindrical perfect fluid. The collapse speed was assumed to be large and the problem was treated approximately.

**Nakao**, **Harada**, **Kurita,** and **Morisawa** studied the implosion of a dust cylinder. The result is not a cylindrical black hole, but a naked singularity.

**Nariai** studied a simple collapsing model with a pressure gradient but no energy flow. The model is regular everywhere, internal events can be perceived by external observers.

**Nariai.** The problem of the linking condition was investigated anew in a further paper.

**Nariai** and **Tomita** [considered the collapse of a star with uniform density and negligible pressure. Neutron emission takes place uniformly inside the star. The model builds on the theory of Oppenheimer and Snyder.

**Nariai** and **Tomita** found a new exterior solution for the model of Oppenheimer and Snyder. This is singularity-free and was adapted to the interior OS solution using the method of O'Brien and Synge.

**Nariai** and **Tomita** found a system consisting of an interior and exterior solution connected by the O'Brien-Synge linking condition. They can describe a collapse or an anti-collapse.

**Narlikar** and **Vaidya** analyzed Walker's isotropy conditions and extended them for the case $T_{14} \neq 0$. They do not give time to a physical application.

**Narlikar** briefly described a spherical nonstatic solution with an electromagnetic field. The mass is position and time-dependent.

**Narlikar** and **Vaidya** found a spherical nonstatic electrovac solution.

**Nogueira** and **Chan** studied a collapsing radiating star with shear and bulk viscosity and emission. At the beginning of the collapse, the pressure is isotropic, but becomes isotropic as a consequence of the viscosity.

**Nolan** keeps an eye on the McVittie solution with a time-dependent mass density approach but extends his investigations to a tachyonic fluid in the region $r < 2M$.

**Nolan** found the gravitational collapse of an asymptotically flat cylinder and prolate dust shells admitting naked singularities.

**Nolan** and **Mena** found further results concerning singularities that arise when inhomogeneous dust collapses. They studied geodesics emanating from the singularities.

**Novikov**. For a collapse below the event horizon, the collapse can become an expansion by changing to the procedure used with a charged sphere.

**Ohashi** and **Shiromizu** studied a spherical collapse of an inhomogeneous dust cloud in Lovelock's theory.

**Ohashi** and **Shiromizu** studied a spherical collapse of a charged inhomogeneous dust cloud in Lovelock's theory.

**Oliveira**, **Kolassis,** and **Santos** extended an earlier model of a collapsing radiating star without assuming any special initial condition.

**Oppenheimer** and **Volkhoff** developed a model for a neutron star. At the end of their work, they express the hope that a solution to a collapse can be found that will slow down over time so that a quasi-stable state can be reached. This problem has been solved by our collapsing interior Schwarzschild solution model.

**Ori** and **Piran** presented a general relativistic solution for a self-similar collapse of an adiabatic perfect fluid. They dealt with cosmic censorship and naked singularities.

**Ori** and **Piran** studied self-similar solutions for a spherical gravitational collapse of a perfect fluid with a barotropic equation of state. This creates naked singularities. They solved Einstein's field equations using numerical methods and calculated radial and non-radial geodesics.

**Pant** and **Tewari** considered time-dependent spheres consisting of a perfect fluid with emission of matter. The model has no horizon.

**Pant** and **Tewari** presented a conformally planar metric describing a symmetric distribution of matter with radiated energy in the form of photons and neutrinos.

**Pant**, **Mehta,** and **Tewari** presented a new class of non-singular solutions representing time-dependent spherical perfect fluids with matter radiation. The class is useful for the interior of a quasar and is connected to the Vaidya metric. Some variables remain undetermined.

**Penna** described the collapse of a pressure-free shell onto a pre-existing black hole, where an observer at infinity never experiences the shell or the event horizon as penetrable. The shell seems to freeze outside the black hole. The inner and outer surface of the shell takes on a certain value late in the collapse.

**Penrose** assumed that in a gravitational collapse the body collapses below the event horizon to form a singularity in finite time for a comoving observer. For an outside observer, the star is contracting infinitely slowly to the event horizon. He also found that deviations from spherical symmetry cannot prevent singularities. After contracting below the event horizon, a spacelike sphere resides in the void region around matter (trapped surface).

**Penrose** claimed that an observer following a free-falling collapse reaches the event horizon after finite time. To support this view, he transforms the Schwarzschild line element into the Eddington-Finkelstein form. The actual Schwarzschild singularity is said to be not at $r = 2M$, but at $r = 0$. He illustrates his argument through light cones.

**Penrose** discussed at length singularities and naked singularities and the validity of cosmic censorship.

**Pereira** and **Wang** assumed two arbitrary cylindrical regions connected by a thin dynamic shell. The shell consists of counter-rotating particles that emit gravitational waves and massless particles as the shell expands or collapses. Depending on the angular momentum of the dust particles, a singularity is created on the axis of symmetry.

**Petrich**, **Shapiro,** and **Teukolsky** studied the Oppenheimer-Snyder collapse in isotropic coordinates using the Arnowitt-Deser-Misner 3+1 formalism. The inner region is treated like the closed Friedman model, the outer region fills the Schwarzschild field. Open parameters are determined by the linking conditions of the regions.

**Pinheiro** and **Chan** studied a radiating collapsing star using thermal viscosity and radial heat flow. The time-dependent metric coefficients lead to a collapse of the system.

**Pinheiro** and **Chan** studied the collapse of a charged body with outward radiation using the Vaidya-Reissner-Nordstrom metric. The charge delays the formation of a black hole and could also prevent a collapse.

**Podurets** prepared a system for numerical calculations involving particles within a variable radius. The mass of the stars is conserved.

**Rahman** claimed that the region within the event horizon does not contain the matter responsible for the collapse. He justified his view with a topology change in the collapse.

**Rajah** and **Maharaj** treated the collapse of a spherically symmetric fluid with heat flow. The governing equation is the Riccati equation.

**Roman** and **Bergmann.** A singularity-free interior solution of a spherically symmetric cloud of matter was presented.

**Rao** looked for the conditions for time-dependent solutions for which an embedding of class one is possible.

**Rao** studied the collapse of a spherically symmetric fluid with spatial isotropy and uniform density. A singularity emerges.

**Raychaudhuri** treated the dynamics of a charged dust distribution. When collapsed, the surrounding region may exhibit oscillatory properties. All treated static solutions have a singularity at the center. He was able to connect a static solution to a Schwarzschild field on one side and to a Reissner-Nordstrom field on the other side.

**Rein**, **Rendall,** and **Schaeffer** used numerical methods to show how collisionless matter falls into a black hole.

**Rocha** studied the collapse of rotating thin shells and made conclusions about cosmic censorship. Higher dimensions were also considered.

**Rosales** et al. used a post-quasistatic approximation and an iterative method to search for the evolution of charged distributions. The electric charge creates anisotropy. The model was linked to an external Reissner-Nordstrom-Vaidya solution.

**Santos** studied the liking conditions for a shear-free isotropic fluid with radial heat flow and unpolarized radiation. He argued with the exterior curvature at the boundary and referred to the linking condition of Lichnerowicz and O'Brien-Synge.

**Santos** continued to treat the radiative, viscous, collapsing fluid proposed by Lake. Equations of state significantly affect the final state of the collapse.

**Sarwe** and **Tikekar** formulated relativistic equations governing a non-adiabatic shear-free collapse of a massive superdense star in the presence of dissipative forces.

**Schäfer** and **Goenner** considered a spherically symmetric object that radiates its mass with constant luminosity. The body starts with infinite mass and radius and contracts to zero without forming an event horizon.

**Scheel** and **Thorne** discussed the possibility of naked singularities in a lengthy paper on black holes.

**Shapiro** and **Teukolsky** numerically explored the rotational effect on the collapse of a collisionless gas spheroid. The spheroid was originally oblate and consisted of the same number of co-rotating and counter-rotating particles. If the spheroids are sufficiently compact, the singularities will be hidden in a black hole. If the spheroids are large enough, there is no apparent horizon.

**Shapiro** and **Teukolsky** presented computer code to describe the collapse of neutron stars and also black holes.

**Shapiro** and **Teukolsky** showed that collision-free gas spheroids collapse into singularities. If the spheroids are sufficiently compact, black holes will form, and if they are sufficiently large, an apparent horizon. Numerical methods were used.

**Sharif** and **Ahmad** studied the collapse of two cylindrical perfect fluids. The collapse takes place at high speed and is calculated approximately. Naked singularities can arise.

**Sharif** and **Abbas** studied the collapse of a charged cylindrical fluid and discussed the physical properties.

**Sharif** and **Siddqa** derived a collapse from a plane-symmetric charged Vaidya metric. The weak energy condition is always fulfilled for the collapsing fluid. Naked singularities emerge. This is a counterargument to the cosmic censorship hypothesis.

**Sharif** and **Siddqa** studied the dynamics of a non-adiabatic flow of an electrically charged fluid. The linking conditions to the exterior Vaidya solution were derived.

**Sharif** and **Iqbal** considered a spherically symmetric collapse with lapse function =1 and Israel's linking condition. The stress-energy-momentum tensor was set up using the external curvature.

**Sharif** and **Fatima** assumed axial symmetry for the interior. The interior is matched to the charged exterior using Darmois' method. Matter dissipation takes place in the form of shear viscosity. The influence of the charges and the dissipative quantities on the cylindrical collapse were studied.

**Sharif** and **Bhatti** considered a non-adiabatic flow of a fluid that has dissipation in the form of shear viscosity and electromagnetic field.

**Sharif** and **Abbas** studied a collapse using the Misner-Sharp formalism. They referred to a non-viscous, anisotropic, charged fluid with heat flow and cylindrical symmetry.

**Sharif** and **Tahir** studied the dynamics of a spherical star with anisotropic pressure, heat flow, shear-viscosity, and radial 4-velocity. They found an evolution equation for the shears.

**Sharma** et al. studied an axisymmetric star collapse with the emission of radiation in the AdS universe. The evolution of the star depends on the initial conditions of the originally static configuration. Either a black hole forms or the star evaporates all of its mass before reaching a singularity.

**Sharma**, **Mukherjee,** and **Maharaj** found a simple scaling property for the mass-radius relation for cold compact stars. The model can be applied to stars with exotic matter or quark stars with parts of vacuum energy.

**Sharma** and **Tikekar** compared the collapse of a star composed of perfectly homogeneous fluid to a star with imperfect fluid and anisotropic pressure.

**Sharma** and **Tikekar**. A non-adiabatic collapse of a shear-free star with anisotropic stresses and radial heat flow was studied. When all of the mass is radiated away, a singularity is formed without an event horizon.

**Singh** wrote a review article on gravitational collapse, black holes, and naked singularities.

**Singh** and **Pandey** investigated the circumstances in which an embedding of class one is possible, whereby the metric coefficients can also be time-dependent.

**Singh** and **Joshi** investigated how the initial density and the velocity distribution affect a collapse of a spherical dust cloud. Three free functions of a Bondi-Tolman metric are determined by the initial conditions. Either a black hole or a naked singularity is formed.

**Singh** and **Witten** studied the gravitational collapse of a compact object where the radial pressure is approximately zero and the tangential pressure is related to the mass density via the equation of state. A space-like singularity is created.

**Smoller** and **Temple** showed that under certain assumptions for the equation of state, black holes never arise as a solution to the Oppenheimer-Volkhoff equation. The pressure will be infinite before is $r = 0$.

**Som** and **Santos** presented a conformal-plane solution of Einstein's field equations that expands. The time-varying variables are not explicitly specified.

**Stephani** found new collapsing/expanding solutions for perfect fluids. They contain arbitrary functions of time and one additional parameter.

**Sussman** analyzed a wide variety of non-static spherical symmetric charged shear-free fluid configurations. He listed known solutions by other authors, along with the undetermined parameters of the solutions.

**Sussman** studied the formation of a black hole in the Friedmann universe, using the same coordinates for both regions. Comoving and Kruskal coordinates for the curvature parameters $k=1$ and $k=0$ were used. He continued the investigations in two follow-up works.

**Sussman** examined in more detail the previously found and already known solutions, which can also be time-dependent. The question of regularity in the center and at the boundary was examined in more detail.

**Szekeres** referred to the Oppenheimer-Snyder solution and criticized the discontinuity of the 1st derivatives of the metric at the boundary. He claimed to have found a coordinate system that covers both the interior and exterior of the solution and therefore avoids linking problems. These comoving coordinates have already been found by Lemaître and do not allow any new conclusions.

**Szekeres** extended a spherical model to a quasi-spherical one. Depending on the initial condition, a black hole is hidden behind the event horizon or a naked singularity.

**Szekeres** and **Iyer** studied a dust collapse that is more general than the class of all collapsing Tolman-Bondi models. The stress-energy-momentum tensor was calculated near the singularity, which can also be a naked one.

**Taub** studied collapsing, expanding, and oscillating models. He found interior solutions, but they are rather unconcerned with the interior Schwarzschild solution.

**Terno** draw information from the stress-energy momentum tensor near the apparent horizon about the collapse of a homogeneous model. Such a model cannot describe a black hole.

**Tewari** and **Charan** found a class of exact solutions to Einstein's field equations for a spherically symmetric anisotropic collapsing fluid with heat flow. The interior solution is connected to the exterior Vaidya solution.

**Tewari** and **Charan** presented a new model with dissipative energy without a horizon. The inner matter is shear-free, isotropic, and spherically symmetric. The interior solution is linked to the exterior Vaidya solution.

**Tewari** and **Charan** found a class of exact solutions to Einstein's field equations for a spherically symmetric anisotropic collapsing fluid with radial heat flow. The interior solution is connected to the exterior Vaidya solution. The radius of mass is initially infinite and then contracts to a point without producing an event horizon. Since the model started collapsing from the infinite past and continued into the finite present, the model can be called an eternal collapse.

**Thirukkanesh**, **Rajah,** and **Maharaj** proposed a collapsing solution in the most general form. They solved the problem with a Riccati-type differential equation, which they further specialized under certain assumptions. The remaining parameters should be chosen with a physical interpretation in mind.

**Thirukkanesh**, **Rajah,** and **Maharaj** treated a radiating star with accelerated, expanding, and shearing matter. By integrating the linking condition, they obtained three new solutions.

**Thirukkanesh** and **Govender**. The effect of charge on a sheared radiating sphere was studied. The linking condition to the exterior Vaidya-Reissner-Nordstrom solution leads to the time evolution equation at the boundary of the collapsing star.

**Thompson** and **Whitrow** studied a gravitational collapse with nonzero pressure and time-dependent energy density. From the point of view of a comoving observer, the object continuously collapses to a point of infinitely high mass density. From the point of view of the non-comoving observer, the object contracts asymptotically towards the event horizon. They introduced a limiting condition for the time dependence of the metric coefficients, so that an analytical solution to Einstein's field equations is possible. They settled open parameters via approximations. In follow-up work, they considered the inner horizon $r=2.25\,M$. But they assumed that the object contracts to a zero volume at this location.

**Thompson** and **Whitrow** set the radius of a spherically symmetrical body with a uniform mass density as a function of time. The equation of state at the center is arbitrary, but the equation of state at any other point is determined by that at the center. The approach is valid for collapsing, expanding, or pulsating models.

**Thorne** discussed a non-singular collapse, e.g. of cylindrical objects, and is critical concerning black holes.

**Tikekar** and **Patel** studied the dynamic equation of a non-adiabatic collapse in the presence of charge.

**Tomita** and **Nariai** derived a model of an oscillating perfect fluid sphere with uniform density.

**Torres** and **Fayos**. Due to quantum effects, a closed 3-horizon was found in a collapse. Hawking radiation is generated at this horizon, whereby total evaporation is possible.

**Unnikrishnan** presented a physically motivated proof of cosmic censorship in the case of Tolman-Bondi pressureless dust collapse.

**Unnikrishnan** studied the dynamic collapse of an inhomogeneous dust and showed that the cosmic censorship is robust and counterexamples are untenable.

**Unruh** contradicted Lake and Hellaby and showed that their model does not contradict cosmic strong censorship.

**Vaidya** wrote down a metric describing a radiation field. The radiation is directed towards the center of the fluid. Their energy is taken from the cosmos.

**Vaidya** studied collapsing radiating matter. Using two mathematical assumptions, he arrived at a model similar to the Oppenheimer and Snyder solution. Two functions remain open. However, they can be adjusted via the linking condition of the time-like metric coefficients. The second linking condition was not addressed.

**Veroni** and **da Silva** were interested in the development of a fluid with heat flow, bulk viscosity and anisotropic pressure. Mass loss occurs during collapse.

**Vickers** studied a charged interior solution with time dependent area coordinate. It is connected to the exterior Reissner-Nordstrom solution. The solution contains three arbitrary time-dependent functions.

**Villas da Rocha,** and **Wang** studied a collapse in higher-dimensional spherical spaces. The collapse has continuous self-similarity. Black holes are created with zero mass.

**Volkhoff** referred to the original Schwarzschild solution and mentioned the property that in this model the pressure can become infinite at a certain radius. He extended the model with a significantly more complicated expression for the pressure inside the object.

**Wagh** et al. reported a spherically symmetric shear-free solution to Einstein's field equations with heat flow. The equation of state has barotropic form. Density, pressure, and heat flow decrease toward the surface of a star.

**Wagh** considered a spherically symmetric Petrov-type D model with a hyperplane-normal radial homothetic Killing vector. He also considered a source-free electromagnetic field in this model.

**Wahlquist** and **Estabrook.** Both collapse and explosion of a central body have been studied. Linking conditions under appropriate coordinates support the model. They used the interior and exterior Schwarzschild solution and the Oppenheimer and Snyder model.

**Waugh** and **Lake** studied marginally bound self-similar Tolman spacetimes and black hole conditions.

**Wilson** studied the dynamics of a collapsing star. The neutrino flux was calculated and it was determined whether the energy flow of the neutrinos can cause mass ejection.

**Wyman** extensively studied non-static radially symmetric solutions of Einstein's field equations. Above all, he tried to find exact solutions.

**Yodzis** et al. discussed the occurrence of naked singularities during dust cloud collapse. For this object, they faced an approach that differs significantly from the interior Schwarzschild solution. The radial variable and mass densities are time dependent. They mentioned that the linking condition to the exterior Schwarzschild solution is fulfilled, but they did not explain this. The pressure-free version with $g_{44} = 1$ suggests that the collapse occurs in free fall. For a version with pressure, the lapse function is $\neq 1$. The collapse for this version is not in free fall.

**Zhang** and **Lake** claimed that naked singularities of a radiating composite sphere arise. If the particles interact strongly, the final state immediately becomes singular.

**Zhang** et al. investigated the possibility that Nature allows black holes. They envisaged a bounce, whereby afterward the collapse the model expands to infinity.

**Ziaie**, **Atazadeh,** and **Tavakoli** studied a collapse for the Brans-Dicke theory with barotropic equation of state. The cosmic censorship conjecture is violated. The collapse rate and the Brans-Dicke scalar field determine the formation of a black hole or naked singularity.

**Ziaie**, **Atazadeh,** and **Rasouli** studied a collapse with barotropic equation of state in f(R) theories of gravity. Under certain conditions naked singularities arise.

**Zhou** et al. studied a spherically symmetric collapse of a dust cloud in 3rd order Lovelock gravity. They obtained three families of LTB-like solutions: hyperbolic, parabolic, and elliptical. Massive naked time-like singularities emerge.

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